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Changes in soil organic carbon and total nitrogen stocks along a chronosequence of *Caragana intermedia* plantations in alpine sandy land

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ABSTRACT

Accurate assessment of soil organic carbon (SOC) and total nitrogen (TN) stocks and analyzing the main influencing factors after revegetation for restoration of sandy soils in alpine regions are important for formulating sustainable management measures and understanding the role of revegetation in mitigating climate change. This study compared SOC and TN stocks and their vertical distributions among 6-, 11-, 17- and 31-year-old *Caragana intermedia* plantations and shifting sand dunes. The results showed that SOC and TN stocks significantly increased as plantation age increased, with the 31-year-old stands having the highest SOC stocks (26.73 Mg ha^{-1}) and TN stocks (2.64 Mg ha^{-1}), which were 97.4% and 149.56% higher, respectively, than those of the shifting sand dunes. Compared to the total soil depth, SOC and TN stocks at all stand ages were higher in surface soil (0–20 cm). SOC stocks in the surface soil of the 6-, 11-, 17- and 31-year-old stands were 38.03%, 71.32%, 103.67% and 253.30% higher, respectively, than those in the surface soil of the shifting sand dunes, and TN stocks in the surface soil were 17.03%, 117.96%, 148.93% and 232.06% higher, respectively, than those in the surface soil of the shifting sand dunes. The percentage of the SOC and TN stock in the 0–20 cm soil depth increased significantly as plantation age increased, with the 31-year-old plantation reaching 43.66% and 33.39%, respectively. Redundancy analysis and correlation analysis showed that at 0–20 cm soil depth, aboveground biomass was the main influencing factor for SOC and TN stocks. At 20–80 cm soil depth, fine root biomass and medium root biomass were the main influencing factors for SOC stocks, and medium root biomass was the main influencing factor for TN stocks.

1. Introduction

As the concentration of carbon dioxide (CO_2) and other greenhouse gasses increases, the greenhouse effect and global warming exacerbating climate change have become globally important issues. Finding some approaches to mitigate the concentration of greenhouse gases in the atmosphere is an urgent matter (Wang et al., 2013). Soil is the largest carbon sink of global terrestrial ecosystems, storing approximately 1550 Pg of carbon, which is twice the atmospheric carbon pool (Lal, 2004).

The soil organic carbon (SOC) stock per unit area is normally low in regions affected by desertification; however, the large area of these regions provides them with a potential capacity to be a carbon sink. Desertification is a type of land degradation in arid and semiarid regions (Wang et al., 2006), and approximately 25% of the world's land is affected by desertification (Reynolds et al., 2007). In the past few decades, some effective desertification control measures have been widely used for restoration in China. The establishment of sand-fixing shrub plantations was one of the successful measures (Su et al., 2010). The restoration of shrublands in sandy lands improves soil texture and nutrient recovery, promotes species establishment and stabilizes moving sand dunes (Zhao et al., 2007; Cahill et al., 2009; Huang et al., 2012). Desertification control using shrubs was also reported to effectively decrease wind erosion, promote soil development and enhance soil C sequestration by increasing net primary productivity and root biomass (Su and Zhao, 2003). Restoring degraded ecosystems through revegetation would increase the carbon stocks in soil and biomass and generate significant ecosystem carbon gains (Nosetto et al., 2006).

Some studies found that soil nitrogen significantly increased after leguminous shrub species were established on sandy land (Su et al.,

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2005; Zhang et al., 2013; Li et al., 2017). The soil nitrogen not only has an important impact on soil carbon sinks through the interaction between soil nitrogen and carbon, but also has an important impact on maintaining the ecological function of plantation ecosystem (Reich et al., 2006; Liu et al., 2016). Some studies on the ecological effects of shrub land exist (Wang et al., 2006; Yang et al., 2011; Li et al., 2017), but there are few reports on how shrubs affected soil carbon sequestration after restoration (Piao et al., 2009). Therefore, quantitative assessment of SOC stocks and total nitrogen (TN) stocks and their dynamics is crucial in understanding the carbon sink capacity of terrestrial ecosystems.

The Gonghe Basin on the Tibetan Plateau is seriously affected by desertification, with 91% of the area affected by desertification (Zhang et al., 2009). In this region, shrub afforestation became an effective way to combat desertification (Lu et al., 2009; Gong et al., 2016). *Caragana intermedia* Kuang & H.C. Fu is an important shrub species used in the restoration of shifting sand dunes in the Gonghe Basin. Before *C. intermedia* seeds were planted, straw checkerboard barriers (1 m × 1 m) were established. Some studies conducted on *C. intermedia* plantations in this region showed that the establishment of *C. intermedia* plantations on sand dunes improved soil properties (Li et al., 2014, 2017), resulted in spatial heterogeneity of soil nutrients (Li et al., 2015), and changed water use strategy over time as an adaptation to a semiarid environment (Jia et al., 2012) as well as that the roots are mainly distributed at depths of 10–90 cm (Liu et al., 2012). However, there are few reports on the dynamics of soil carbon and nitrogen stocks in *C. intermedia* plantations. Obtaining reliable information on the carbon and nitrogen changes in soils after vegetation restoration and analyzing the main influencing factors are important for formulating sustainable management measures and understanding the role of revegetation in mitigating climate change. Therefore, the objectives of this study were to (1) estimate SOC and TN stocks for 6-, 11-, 17- and 31-year-old *C. intermedia* plantations across soil depth in alpine sandy land and (2) analyze the main factors influencing SOC and TN stocks.

2. Materials and methods

2.1. Study area

This study was carried out at the desertification combating experimental site of the Qinghai Gonghe Desert Ecosystem Research Station (99°45′–100°30′E, 36°03′–36°40′N and altitude 2871 m), which was constructed by the Desertification Combating Station of Qinghai Province and the Chinese Academy of Forestry (Fig. 1). The mean annual precipitation is 246.3 mm, and more than three-quarters of the precipitation occurs during the growing season from June to September. The mean annual potential evaporation is 1716.7 mm. The mean annual air temperature is 2.4 °C, and the mean annual number of windy days and sandstorm days are 50.6 and 20.7 days, respectively. The mean annual wind speed is 2.7 m·s^{-1}, but the maximum wind speed reaches 40 m·s^{-1}. In the study area, the zonal soils are chestnut soil and brown soils, and the azonal soils are aeolian, meadow and bog soils. The primary vegetation type of study area is sand-fixing plantation, dominated by the tree species *Populus cathayana* Rehd, *Populus simonii* Carr. and shrub species *Hippophae rhamnoides* L. in the site between sand dunes and the shrub species of *C. intermedia*, *Caragana korshinskii* Kom., *Salix cheilophila* Schneid. and *Salix psammophila* C. Wang & Chang Y. Yang on sand dunes (Zhang et al., 2009; Li et al., 2014).

2.2. Experimental design and sampling

This study was carried out in mid-August 2017. Three plots (10 m × 10 m) with similar topographical traits were selected for sampling in 6-, 11-, 17- and 31-year-old pure *C. intermedia* plantations. All selected plantations were sown in lines with line spacing of 2 m. Ten plants were randomly selected for morphological characteristic measurements in each plot, including the height (maximum height (H)), basal diameter (*C. intermedia* is a multiple-stemmed shrub, we measured the thickest stem (D)), and crown diameter (average of maximum and minimum crown diameters). One standard shrub was selected from each plot according to the mean morphological characteristics for different *C. intermedia* plantation ages. The location of the sampling sites and the morphological characteristics of standard shrubs are shown in Table 1.

A total of 12 standard shrubs were selected and harvested for biomass determination. Each individual shrub was separated into leaves, branches and stems, and roots > 5 mm, 2 mm < roots ≤ 5 mm and roots ≤ 2 mm. Root samples of the standard shrubs were obtained by the total soil excavation of a sampling area of 1 m × 2 m, extending out from the one shrub center to the middle of another shrub center. Roots were excavated at 0–20, 20–40, 40–60, and 60–80 cm depths. At each depth, soil samples were also collected from the center of the shrub in four directions at intervals of 10 cm, and all soil samples were uniformly mixed into one sample for SOC and TN determination, after passing through a 0.6 mm sieve to separate roots. The samples of every component from each standard shrub were oven dried at 65 °C for 48 h to obtain dry biomass. In addition, three shifting sand dunes without vegetation were selected as the control sites, and soil samples were collected randomly at depths of 0–20, 20–40, 40–60, and 60–80 cm. A total of 60 soil samples were collected, 48 soil samples were collected in plantations (4 ages × 3 replicates × 4 soil depths), and 12 soil samples were collected on sand dunes (3 replicates × 4 soil depths). To calculate the stock of SOC and TN at each depth, soil bulk density was estimated using the core method (a cylindrical metal 100 cm^3 corer) with three replicates at each depth. The soil samples were dried at 65 °C for more than 24 h until they reached a constant weight.

2.3. Soil laboratory analysis and SOC and TN stocks calculation

Soil samples were air-dried and passed through a 0.25 mm sieve. The potassium dichromate and sulfuric acid method was used for the determination of soil organic carbon. The semimicro-Kjeldahl method was used for the determination of total nitrogen. All analyses were based on the Physical and Chemical Analysis Methods for Soils (Institute of Soil Sciences, Chinese Academy of Sciences (ISSCAS), 1978). The following formulae were used for estimating SOC and TN stocks (Mg ha^{-1}) (Wang et al., 2016):

$$SOC\ stocks = \sum_{i}^{m} SOC_i \times B_i \times H_i \times 10 \tag{1}$$

$$TN\ stocks = \sum_{i}^{m} TN_i \times B_i \times H_i \times 10 \tag{2}$$

where SOC$_i$ is the soil organic carbon concentration on the *i*th layer (g kg^{-1}), TN$_i$ is the total nitrogen concentration on the *i*th layer (g kg^{-1}), B$_i$ is the bulk density of the *i*th layer (g cm^{-3}), H$_i$ is the thickness of this layer (m), and 10 is the coefficient of unit conversion.

2.4. Data analysis

The effects of plantation age, soil depth and their interactions on SOC and TN stocks in *C. intermedia* plantations were analyzed by two-way ANOVA. Comparisons of SOC and TN stocks among four plantations, shifting sand dunes and four soil depths were tested by one-way ANOVA and Duncan's multiple range test. The correlation between SOC stocks, TN stocks and morphological and biomass characteristics of *C. intermedia* plantations were analyzed by correlation analysis. All the above statistical analyses were conducted using SPSS 16.0 software.

Unlike in the shifting sand dunes, *C. intermedia* is the main factor directly or indirectly leading to changes in SOC and TN stocks at

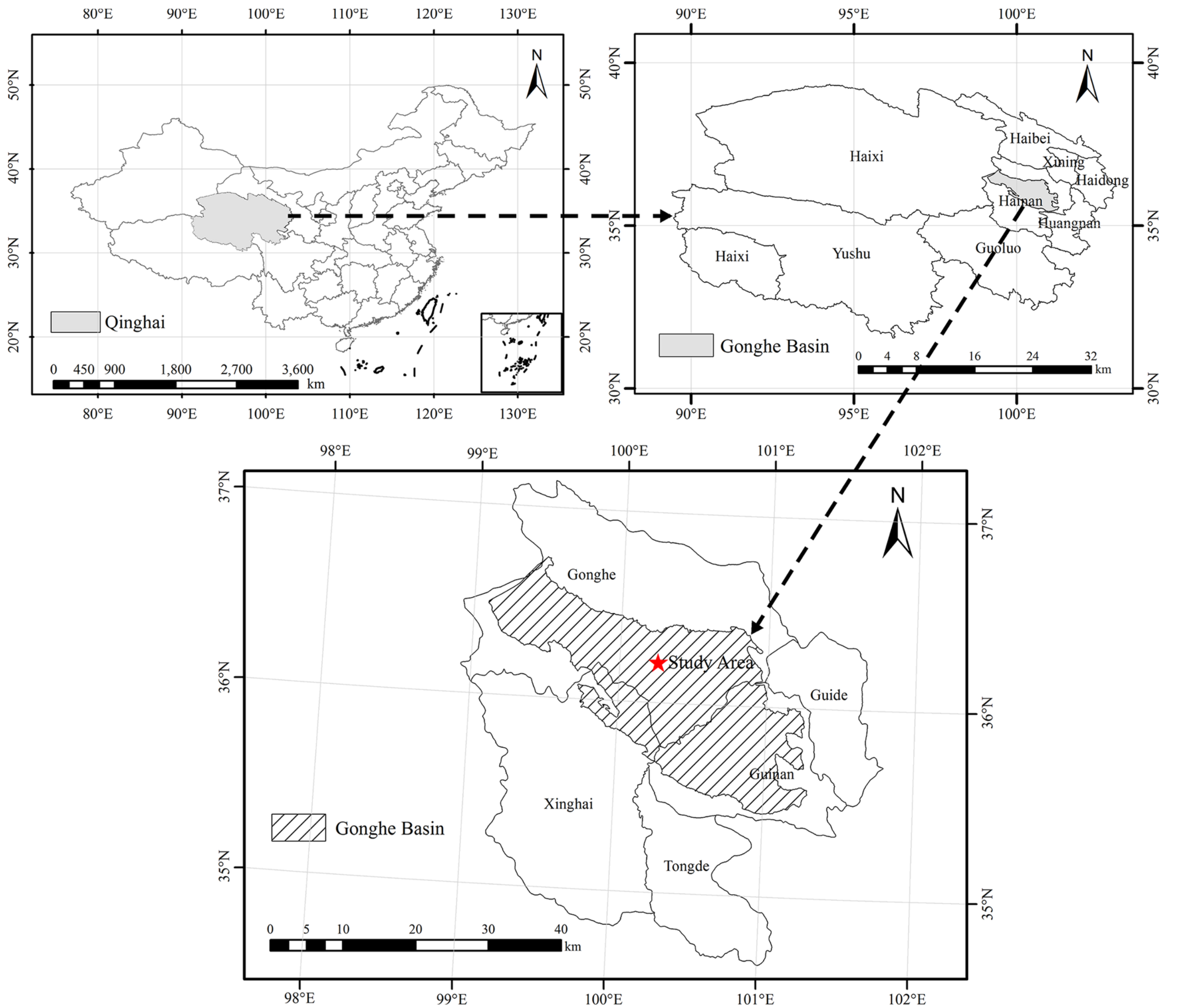

Fig. 1. Location of the study area, Gonghe County, Qinghai Province, China.

Table 1
The location of the sampling sites and the morphological characteristics of standard shrubs for different ages of *C. intermedia* plantations.

Stand age (Years)	Location	Height (cm)	Basal diameter (cm)	Crown diameter (cm)
CK	N36°14′05″; E100°14′36″			
6	N36°14′10″; E100°14′35″	95.33 ± 12.45	0.91 ± 0.01	138.50 ± 7.29
11	N36°14′44″; E100°13′30″	115.00 ± 5.77	1.46 ± 0.03	132.17 ± 6.83
17	N36°15′08″; E100°14′01″	167.33 ± 4.33	1.56 ± 0.07	158.00 ± 1.00
31	N36°14′51″; E100°13′48″	163.33 ± 7.26	1.38 ± 0.08	150.50 ± 4.73

CK: shifting sand dune. Values are the mean ± SE (n = 3).

different plantation ages. Therefore, the morphological and biomass characteristics of *C. intermedia* plantations were selected as environmental factors (height (H), crown diameter (CD), basal diameter (BD), leaf biomass (LB), branch biomass (BB), stem biomass (SB), fine root biomass (FRB, roots ≤2 mm), medium root biomass (MRB, 2 mm < roots ≤ 5 mm), and coarse root biomass (CRB, roots > 5 mm)). The relationship between SOC and TN stocks and environmental factors was evaluated by redundancy analysis (RDA). The statistical significance was tested by the Monte Carlo permutation method based on 499 runs with randomized data, and this statistical analysis was conducted using CANOCO 4.5 software.

3. Results

3.1. Temporal and spatial variation of SOC and TN stocks in C. intermedia plantations

The two-way ANOVA showed that SOC and TN stocks were significantly affected by plantation age and soil depth as well as their interactions (Table 2). There was no significant difference in SOC and TN stocks at different depths in shifting sand dunes and 6-year-old plantations ($P > 0.05$) (Table 3). In 11- and 17-year-old plantations, SOC stocks at the 0–20 cm depth were significantly higher than those at

Table 2
Two-way ANOVA F and P-values for the effects of plantation age (Y), soil depth (D) and the interaction of Y and D (Y × D) on soil organic carbon (SOC) stocks and total nitrogen (TN) stocks.

	Y		D		Y × D	
	F	P	F	P	F	P
SOC stocks	66.83	< 0.001	75.58	< 0.001	16.75	< 0.001
TN stocks	100.02	< 0.001	9.06	< 0.001	3.13	< 0.001

other soil depths ($P < 0.05$). In 31-year-old plantations, SOC stocks significantly decreased ($P < 0.05$) with depth 0–20 cm > 20–40 cm > 40–60 cm > 60–80 cm depth. In 11-, 17- and 31-year-old plantations, TN stocks at the 0–20 cm depth were significantly higher than those at other soil depths ($P < 0.05$). The percentage of the SOC stock in the surface soil of the shifting sand dunes as well as 6-, 11-, 17- and 31-year-old plantations was 24.40%, 31.16%, 32.54%, 35.67% and 43.66%, respectively, and the percentage of the TN stock was 25.09%, 26.70%, 25.71%, 29.36% and 33.39%, respectively (Figs. 2 and 3).

At a depth of 0–20 cm, the SOC and TN stocks significantly increased as plantation age increased ($P < 0.05$) (Table 3), and SOC and TN stocks increased from 3.30 Mg ha^{-1} and 0.27 Mg ha^{-1}, respectively, in shifting sand dunes to 11.67 Mg ha^{-1} and 0.89 Mg ha^{-1}, respectively, in a 31-year-old plantation. SOC stocks in surface soil in 6-, 11-, 17- and 31-year-old stands were 38.03%, 71.32%, 103.67% and 253.30% higher, respectively, than in shifting sand dunes, and TN stocks were 17.03%, 117.96%, 148.93% and 232.06% higher, respectively, than in shifting sand dunes. At depths of 20–40 cm, 40–60 cm and 60–80 cm, the SOC and TN stocks of the 31-year-old plantation were significantly higher than those of the shifting sand dunes and the other plantations ($P < 0.05$). SOC stocks in the 6-year-old plantation were 2.62%, 1.33% and 0.83% lower than those in the shifting sand dunes at the 20–40 cm, 40–60 cm and 60–80 cm depths, respectively. SOC stocks in the 11-, 17- and 31-year-old plantations at 20–40 cm, 40–60 cm and 60–80 cm depths were higher, and TN stocks were significantly higher than in the shifting sand dunes. At 0–80 cm depth, SOC stocks of the 6-, 11-, 17- and 31-year-old plantations were 8.07%, 28.42%, 39.29% and 97.43% higher than those of the shifting sand dunes, while TN stocks were 9.99%, 112.74%, 112.74% and 149.56% higher than those of the shifting sand dunes, SOC and TN stocks at 0–80 cm depth ranged from 14.63 to 26.73 Mg ha^{-1} and 1.17 to 2.64 Mg ha^{-1}, respectively, in all plantations (Table 3).

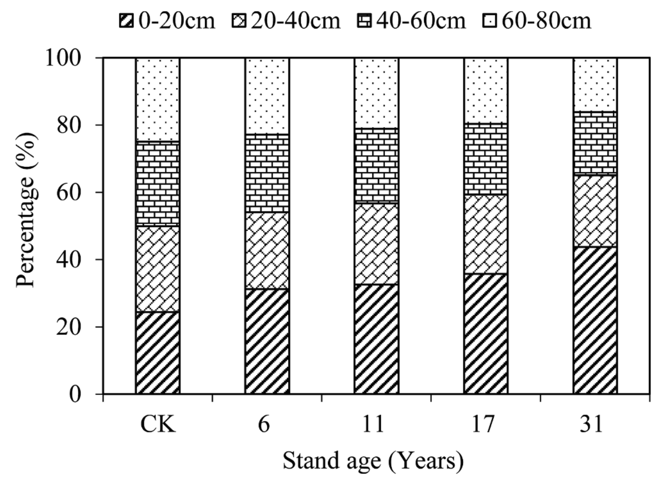

Fig. 2. Percentage of soil organic carbon (SOC) stocks of each layer for the shifting sand dunes and for the different ages of *C. intermedia* plantations (%).

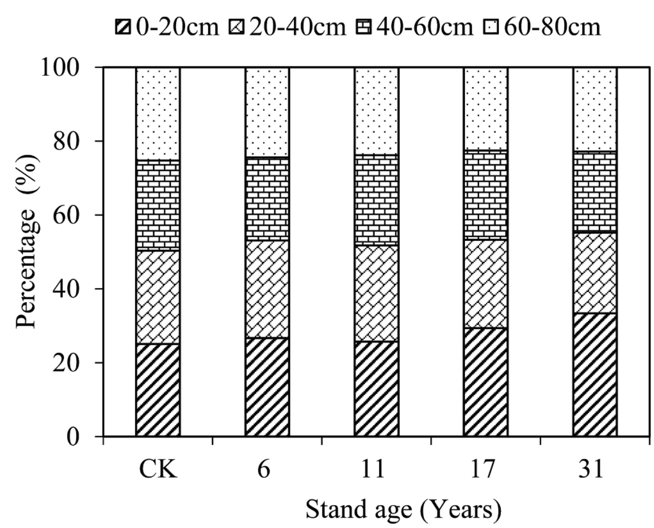

Fig. 3. Percentage of total nitrogen (TN) stock of each layer for the shifting sand dunes and for the different ages of *C. intermedia* plantations (%).

Table 3
Soil organic carbon (SOC) stocks and total nitrogen (TN) stocks at different soil depths for shifting sand dune (CK) and the different ages of *C. intermedia* plantations (Mg ha^{-1}).

	Depth (cm)	Plantation Age (Years)				
		CK	6	11	17	31
SOC stocks	0–20 cm	3.30 ± 0.10Aa	4.56 ± 0.53ABa	5.66 ± 0.32BCb	6.73 ± 0.89Cb	11.67 ± 0.14Dd
	20–40 cm	3.45 ± 0.27Aa	3.36 ± 0.12Aa	4.19 ± 0.34ABa	4.45 ± 0.14Ba	5.71 ± 0.32Cc
	40–60 cm	3.41 ± 0.53Aa	3.37 ± 0.22Aa	3.86 ± 0.06Aa	3.96 ± 0.13Aa	5.02 ± 0.18Bb
	60–80 cm	3.38 ± 0.22Aa	3.35 ± 0.21Aa	3.68 ± 0.11Aa	3.72 ± 0.06Aa	4.32 ± 0.07Ba
	0–80 cm	13.54 ± 0.81A	14.63 ± 1.06AB	17.39 ± 0.80BC	18.86 ± 1.16C	26.73 ± 0.69D
TN stocks	0–20 cm	0.27 ± 0.01Aa	0.31 ± 0.02Aa	0.58 ± 0.03Ba	0.66 ± 0.03Bb	0.89 ± 0.07Cb
	20–40 cm	0.27 ± 0.02Aa	0.31 ± 0.04Aa	0.59 ± 0.06Ba	0.54 ± 0.02Ba	0.58 ± 0.01Ba
	40–60 cm	0.26 ± 0.01Aa	0.26 ± 0.03Aa	0.55 ± 0.07Ba	0.55 ± 0.05Ba	0.58 ± 0.01Ba
	60–80 cm	0.27 ± 0.02Aa	0.29 ± 0.01Aa	0.54 ± 0.02BCa	0.51 ± 0.02Ba	0.61 ± 0.04Ca
	0–80 cm	1.06 ± 0.04A	1.17 ± 0.10A	2.26 ± 0.18B	2.26 ± 0.12B	2.64 ± 0.22C

CK: shifting sand dune; different uppercase letters following values indicate a significant difference in SOC and TN stocks at different ages of plantations; different lowercase letters following values indicate a significant difference in SOC and TN stocks at different soil depths, according to Duncan's multiple range test ($P < 0.05$), n = 3.

Table 4
Canonical coefficients of environmental factors for the first two axes of the RDA at depths of 0–20 cm and 20–80 cm.

Variables	0–20 cm		20–80 cm	
	Axis1	Axis2	Axis1	Axis2
H	0.722	0.331	−0.711	0.093
CD	0.398	0.119	−0.309	0.194
BD	0.444	0.681	−0.718	−0.517
LB	0.937	0.005	−0.788	0.407
BB	0.923	−0.063	−0.746	0.476
SB	0.908	−0.101	−0.732	0.461
FRB	0.734	−0.070	−0.807	0.455
MRB	0.621	0.050	−0.917	0.253
CRB	0.770	0.231	−0.829	0.308
Eigenvalues	0.973	0.022	0.888	0.082
Accumulated variance percentage	97.3	99.5	88.8	97.0

H: Height; CD: Crown diameter; BD: Basal diameter; LB: Leaf biomass; BB: Branch biomass; SB: Stem biomass; FRB: Fine root biomass (roots ≤2 mm); MRB: Medium root biomass (2 mm < roots ≤ 5 mm); CRB: Coarse root biomass (roots > 5 mm).

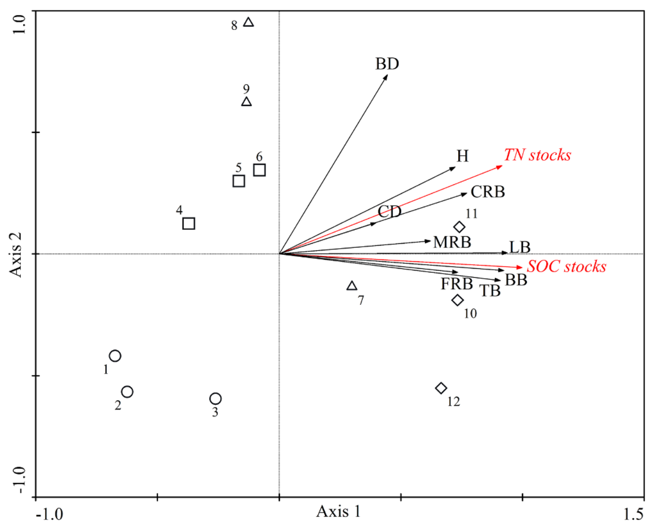

Fig. 4. Ordination diagram of RDA on SOC and TN stock concentrations with environmental factors at 0–20 cm depth. The numbers 1, 2, and 3 represent 6-year-old plantation; 4, 5, and 6 represent 11-year-old plantation; 7, 8, and 9 represent 17-year-old plantation and 10, 11, and 12 represent 31-year-old plantation. H: Height; CD: Crown diameter; BD: Basal diameter; LB: Leaf biomass; BB: Branch biomass; SB: Stem biomass; FRB: Fine root biomass (roots ≤2 mm); MRB: Medium root biomass (2 mm < roots ≤ 5 mm); CRB: Coarse root biomass (roots > 5 mm).

3.2. Effects of environmental factors on SOC and TN stocks

The SOC and TN stocks of *C. intermedia* plantations in surface soil increased significantly with increasing plantation age compared with other soil depths. The 0–80 cm soil depth was divided into 0–20 cm and 20–80 cm depths for analyzing the effects of environmental factors. The relationship between SOC and TN stock variables and environmental variables at depths of 0–20 cm and 20–80 cm was assessed through RDA (Table 4, Figs. 4 and 5). The cumulative percentage variance of the dependent variables (SOC and TN stocks)-environment relationship for the first two axes was 99.8% for the 0–20 cm depth and 97.9% for the 20–80 cm depth, indicating that there was a strong association between SOC and TN stocks and environmental factors. Redundancy analysis (RDA) showed that SOC and TN stocks were primarily affected by branch biomass, leaf biomass and stem biomass at a depth of 0–20 cm. At depth of 20–80 cm, SOC stocks were primarily affected by fine root biomass and medium root biomass, and TN stocks were primarily affected by medium root biomass. A more detailed relationship was shown by Pearson correlation analysis (Table 5).

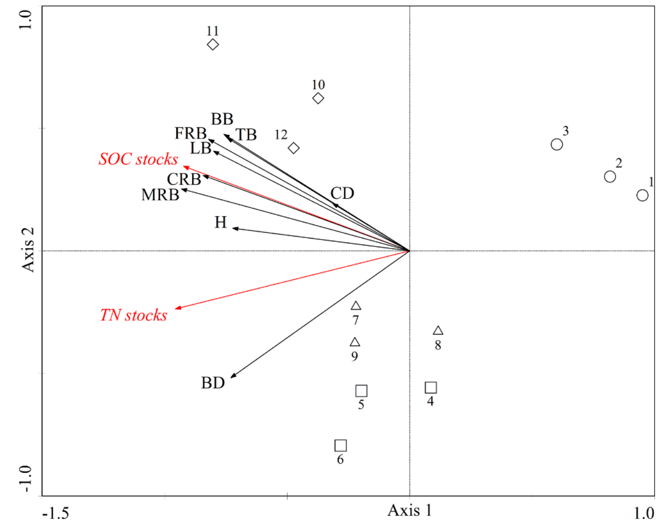

Fig. 5. Ordination diagram of RDA on SOC and TN stock concentrations with environmental factors at 20–80 cm depth. The numbers 1, 2, and 3 represent 6-year-old plantation; 4, 5, and 6 represent 11-year-old plantation; 7, 8, and 9 represent 17-year-old plantation and 10, 11, and 12 represent 31-year-old plantation. H: Height; CD: Crown diameter; BD: Basal diameter; LB: Leaf biomass; BB: Branch biomass; SB: Stem biomass; FRB: Fine root biomass (roots ≤2 mm); MRB: Medium root biomass (2 mm < roots ≤ 5 mm); CRB: Coarse root biomass (roots > 5 mm).

4. Discussion

Vegetation restoration has a significant effect on soil carbon and nitrogen sequestration (Deng et al., 2016). In this study, SOC and TN stocks were significantly increased with *C. intermedia* plantation development in alpine sandy land, which was similar to other studies. For example, Huang et al. (2012) reported that SOC and TN stocks increased significantly after shrub plantation practices in Horqin Sandy Land compared with bare sandy land, with SOC stocks at 0–40 cm depth ranging from 359.2 to 879.74 g m^{-2} in all shrub stands. On the Loess Plateau, SOC stocks of *C. korshinskii* plantations increased remarkably with stand age, and SOC stocks at 0–80 cm depth ranged from 10.59 to 27.94 Mg ha^{-1} from young to mature plantations (Deng et al., 2017).

Some studies show that afforestation usually causes soil carbon and nitrogen to decrease during the first few years and then gradually increase until net carbon gains are generated (Li et al., 2011; Karhu et al., 2011; Mujuru et al., 2014). In this study, the SOC stocks of 6-year-old plantations at 0–20 cm depth were higher than those of shifting sand dunes, whereas at 20–40 cm, 40–60 cm and 60–80 cm depths, SOC stocks were lower than those of shifting sand dunes. However, as the plantation age increased, SOC stocks at deeper soil depths (20–80 cm) significantly increased. It could be that during the initial period of afforestation, the accumulation of soil organic carbon is greater than the consumption in surface soil due to the shallow depth being more influenced by litter and nutrient-rich fine materials (Yang et al., 2011). However, the consumption of SOC may be greater than the accumulation at deeper depths in the initial period of afforestation because only a small part of the decomposed litter enters the deep soil, and the input from fine root death is relatively small in the early stage of afforestation. The nutrients absorbed by shrubs from deep soil may be more than their input (Miao et al., 2014). Laganière et al. (2010) reported that with increasing afforestation time, soil carbon has initial losses of 5.6% during the early stage (< 10 years) and then gains of 6.1 and 18.6% in mature stage (10–30 years) and older stage (> 30 years) plantations, respectively. Mao et al. (2010) also found that both SOC and TN stocks

Table 5
Correlation between soil organic carbon (SOC) stocks and total nitrogen (TN) stocks of each layer and morphological and biomass characteristics of *C. intermedia* plantations.

		H	CD	BD	LB	BB	SB	FRB	MRB	CRB
0–20 cm	SOC stocks	0.670*	0.380	0.322	0.937**	0.941**	0.928**	0.748**	0.587*	0.724**
	TN stocks	0.778**	0.409	0.624*	0.863**	0.829**	0.799**	0.655*	0.565	0.770**
20–80 cm	SOC stocks	0.682*	0.350	0.443	0.880**	0.872**	0.852**	0.927**	0.950**	0.886**
	TN stocks	0.661*	0.245	0.798**	0.668*	0.613*	0.603*	0.683*	0.841**	0.735**

H: Height; CD: Crown diameter; BD: Basal diameter; LB: Leaf biomass; BB: Branch biomass; SB: Stem biomass; FRB: Fine root biomass (roots ≤ 2 mm); MRB: Medium root biomass (2 mm < roots ≤ 5 mm); CRB: Coarse root biomass (roots > 5 mm).
* Correlation significant at the 0.05 level (2-tailed).
** Correlation significant at the 0.01 level (2-tailed).

of poplar stands were lower in the early stage of forest establishment, and then increased with stand development. In this study, after 11 years of *C. intermedia* plantation establishment, SOC stocks at deeper soil depths (20–80 cm) increased with increasing plantations age. This result was consistent with Deng et al. (2014), who reported that after revegetation, the deeper-soil C sequestration function lagged behind that of the surface soil, suggesting that the C sequestration mechanisms in surface and deeper soil are different. TN stocks of *C. intermedia* plantations were significantly higher than those of shifting sand dune. This is likely because there are large amounts of rhizobia in the root of *C. intermedia*, which can fix nitrogen in the atmosphere (Gao et al., 2004). It is possible that the nitrogen fixation capacity of *C. intermedia* increased as plantation age increased; this requires further study to confirm.

The SOC and TN stocks of all plantations were higher in surface soil (0–20 cm) than in deeper soil (20–80 cm). A similar result was reported by Wang et al. (2016), who found that in shrub land, the SOC and TN stocks in surface soil (0–20 cm) account for 43.6% and 46.7%, respectively, of total SOC and TN. Huang et al. (2012) also reported that the surface soil layer (0–20 cm) stores more soil organic carbon than the other layers. Justine et al. (2017) reported that 53.5% of the SOC was stored in the top 0–30 cm soil layers. Deng et al. (2014) found higher rates of soil carbon change at the 0–20 cm soil depth than at lower depths (20–100 cm).

The changes in SOC in shrub lands are primarily affected by above-ground parts and roots (Huang et al., 2012). In this study, above-ground biomass was the main influencing factor for SOC and TN stocks at depth of 0–20 cm probably because leaves are the main source of litter on above-ground, and the branches and stems trapped litter and nutrient-rich fine materials and gathered them on surface soil (Pugnaire et al., 2004). Soil organic carbon and nitrogen returned to surface soil via microbial decomposition (Yang et al., 2011). As the young trees grow older, more biomass accumulates, resulting in increased litter-fall (Mujuru et al., 2014), thus influencing SOC and TN stocks in surface soil. Wang et al. (2016) also found that litter biomass and live above-ground biomass were the primary factors influencing soil organic carbon and nitrogen in surface soil.

At depth of 20–80 cm, fine root biomass and medium root biomass were the main influencing factors for SOC stocks, and medium root biomass was the main influencing factor for TN stocks. The soil organic carbon from fine root mortality and decomposition in the growing season is equal to or even higher than that from leaves in some ecosystems (Gill and Jackson, 2000; Block et al., 2006). Huang et al. (2012) reported that in semiarid degraded lands, the soil carbon from fine root death and decomposition contributes significantly to the recovery of SOC and TN stocks. Another important way for roots to import carbon into the soil is through root exudates (Jones et al., 2009). Paterson (2003) reported that the amount of carbon released from exudates into grassland soils was similar to that generated from root turnover. Guo et al. (2005) also reported that the activity of live fine roots may lead to more soil carbon increase than fine root decomposition in pot-comparing experiments. In this study, medium root biomass is another major influencing factor for SOC and TN stocks, in addition to fine root biomass, at 20–80 cm depths, probably because medium root exudates increased SOC and TN stocks. Further studies are needed to confirm this assumption. Plants allocate more biomass to roots to absorb more soil moisture or nutrients when water or nutrients are the main limiting factors (Osone and Taten, 2005). Low levels of soil nutrients and water are a major feature of alpine sandy land, and there might be significant carbon and nitrogen transfer from plants to soil through root turnover and root exudates in shrub plantations.

5. Conclusions

SOC and TN stocks significantly increased with the development of *C. intermedia* plantations in alpine sandy land, especially in surface soil (0–20 cm). The 31-year-old plantations had the largest SOC stocks and TN stocks which were 97.4% and 149.56% higher, respectively, than the stocks in the shifting sand dunes. The percentages of SOC and TN stocks in the surface soil of the 31-year-old plantation were higher than those in the surface soil of the youngest plantation. The SOC stocks of the 6-year-old plantation in deeper soil (20–80 cm) were lower than those in deeper soil in the shifting sand dunes. Above-ground biomass was the main factor influencing SOC and TN stocks at a depth of 0–20 cm. At a depth of 20–80 cm, fine root and medium root biomass were the main factors influencing SOC stocks, while medium root biomass was the main factor influencing TN stocks. Therefore, the establishment of *C. intermedia* plantations in the sandy land of the Tibetan Plateau has great potential for SOC and TN sequestration. We suggest that the influences of plantation age and soil depth should be taken into account when estimating the SOC and TN storage of plantations.

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